

Neutrino Geophysics at Baksan (Part II): Possible Studies of Antineutrino- and Radiogenic Heat Sources in Earth Interior

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Abstract

Antineutrinos born inside the Earth ("geoneutrinos") carry out information of fundamental importance for understanding of the origin and evolution of our planet. We show that Baksan Neutrino Observatory is one of the best sites for detection and analysis of geoneutrinos using large liquid scintillation spectrometer. Also we present a short story of concept of Earth as antineutrino source (1960 - 2004 yy).

Introduction

In this paper we consider future studies at BNO (Baksan Neutrino Observatory of Institute for Nuclear Research RAS) of terrestrial antineutrinos $\bar{\nu}_e$ coming from beta decay of Uranium and Thorium daughter products ("Geoneutrinos"). Geoneutrinos bring information on the Uranium and Thorium abundances and radiogenic heat sources inside the Earth, which are of a key importance for understanding of the formation and subsequent evolution of our planet [1]. Geoneutrino is a part of future studies at BNO of low energy $\bar{\nu}_e$ fluxes of natural origin aimed for obtaining information on their

sources, which is otherwise inaccessible. For this purpose a large target mass $\bar{\nu}_e$ scintillation spectrometer is planned with the inverse beta decay

$$\bar{\nu}_e + p \rightarrow n + e^+ \quad (1)$$

as the detection reaction.

The program also includes:

- Estimation of frequency of gravitational collapses in the Universe by detection of isotropic flux of $\bar{\nu}_e$, [2, 3].
- Test of the hypothesis that a self-sustaining nuclear chain reaction is burning at the center of the Earth (“Georeactor”) [4–7].
- Search for solar antineutrinos, which can be produced through ^8B neutrino spin-flavor precession.
- We note also that no spectroscopic information has so far been obtained on the solar pep, ^7Be and CNO neutrinos (ν_e). We hope that in this important field progress can be achieved at BNO with ν_e, e scattering as detection reaction.
- Quite recently old ideas [8] on using detection for nuclear reactor control (Plutonium production, nonproliferation etc.) have been revived: (See “Neutrino and Arms Control” 2004, <http://www.phys.hawaii.edu/~jgl/nacw.html>). BNO can join international efforts in this field.

KamLAND Collaboration in Japan, using reaction (1) has recently demonstrated revolutionary progress in $\bar{\nu}_e$ detection technique. KamLAND has already reported that a few geoneutrino events have been observed [9] and moves towards detection of soft solar neutrinos. BOREXINO Collaboration at LNGS, Italy, is planning to start soon experiments in the same direction. Under the circumstances question can be asked: Is it necessary to start new projects in the same field?

As far as geoneutrinos are concerned, the answer is that their flux is expected to depend strongly on the point of observation. The intensity of $\bar{\nu}_e$ is predicted to be maximal at high mountains sites (Himalaya, Caucasus where BNO is situated), to be minimal in the ocean far from continents (Hawaii, and may be Curacao [7]) and have intermediate values in Japan and Italy.

We note also that for success of the experiments listed above the level of the backgrounds is of a decisive importance. To a great degree the background is produced by cosmic muons and by $\bar{\nu}_e$ flux from power reactors. At BNO located at the 4800 mwe rock overburden, the muon flux is much lower than in KamLAND and BOREXINO experiments (Fig. 1). The flux of reactor $\bar{\nu}_e$ at BNO is also 10 and 2 times lower than it is at mentioned laboratory sites respectively [6].

We conclude that BNO is one of the most promising sites to build a massive antineutrino scintillation spectrometer for these studies. Essentially we propose to prepare the next step in low energy antineutrino and neutrino physics, which, using experience accumulated in KamLAND and BOREXINO projects, will provide further progress in the fields discussed here. Importance of this goal is confirmed by recently published idea of LENA experiment [10].

In the next sections we give a short overview of the history of geoneutrino problem, which is now almost 45 years old, next we consider geoneutrino models and will finish with the results we hope to obtain at BNO.

1 Geoneutrinos: First Estimations of Fluxes and Search for Detection Reaction (1960-1984)

Marx and Menyard [11] in 1960 were the first to point out that the Earth is a source of antineutrinos, which are produced in U and Th daughter product beta decay, in decay of ^{40}K and of some other long-lived nuclei. They assumed that natural radioactivity is concentrated in a thin upper layer of the Earth and estimated the $\bar{\nu}_e$ flux at the surface:

$$F \sim 6.7 \times 10^6 \text{ cm}^{-2}\text{s}^{-1}, \quad (2)$$

which is not far from modern values. Radioactivity inside the Earth is unknown. If the concentration were not to decrease with the depth, the flux could be hundred times higher.

“In the far future an experiment will be needed to set an upper limit on the antineutrino activity of the Earth. This probably is the only way to get information on the composition of the substance in the deep layers of the

Earth” wrote M. A. Markov in 1964 [12]. Markov, as far as we know, was the first to mention the process (1) as a possible geoneutrino detection reaction. “Because of high threshold, – he continued, – the number of active $\bar{\nu}_e$ in this case is very low”. He stressed also the importance of finding a detection reaction with lower energy threshold. (Typical geoneutrino energy spectrum is shown in Fig. 2.)

Two years later Eder [13] explained the gradual slowing down of the circulation rate of the Earth and the increase of its radius by a large amount of radiogenic heat sources in the mantel, “sufficient to blow up our planet”. The relevant geoneutrino flux was found two orders of magnitude higher than (2). Eder also mentioned process (1) as a possible detection reaction. No details of detector layout and detection principle were discussed at that early time.

Antineutrinos of sufficiently low energy can, principally, be detected via resonant reactions of induced orbital electron capture in otherwise stable nucleus $A(Z)$ [14]:

$$\bar{\nu}_e + e^- + A(Z) \rightarrow A(Z - 1). \quad (3)$$

The reaction signature can be appearance of radioactive nucleus $A(Z - 1)$ in the irradiated target (radiochemical method). Antineutrinos are captured only in a narrow energy band near the resonant energy $E_{res} \approx T_{max}$, where T_{max} is maximal kinetic energy of the electrons in the decay of $A(Z - 1)$: $A(Z - 1) \rightarrow A(Z) + e^- + \bar{\nu}_e + T$. Clearly, the resonant energy E_{res} is $2mc^2 = 1.02$ MeV lower than the threshold energy in the “usual” inverse beta decay reaction on the same nucleus:

$$\bar{\nu}_e + A(Z) \rightarrow A(Z - 1) + e^+. \quad (3.1)$$

The transition probability w per unite time between initial and final states in reaction (3) can be written as:

$$w \sim (ft)^{-1} |\psi(0)|^2 dF(E_{res})/dE. \quad (4)$$

Here $|\psi(0)|^2$ is the probability density for atomic electron at nuclear surface, ft is the reduced lifetime of beta decay (3.1) and $dF(E_{res})/dE$ $\text{cm}^{-2} \text{s}^{-1} \text{MeV}^{-1}$ is the spectral density of incoming $\bar{\nu}_e$ flux at resonant energy. The density $|\psi(0)|^2$ rapidly increases with atomic number, approximately as Z^3 , the spectral density is high at energies lower than 1.8 MeV (Fig. 2),

the inverse beta decay reaction (3.1) at high Z is suppressed by positron repulsion in the final state. As a result the resonant capture dominates over (3.1) for sufficiently heavy target nuclei.

Potentially, the resonant capture reaction, unlike reaction (1), can search for terrestrial ^{40}K antineutrinos, which is of a vital importance for geophysics.

In 1968 y Markov and Zatsepin organized in Moscow an International Workshop on Neutrino Physics and Astrophysics, which later transformed to regular “NEUTRINO” Conferences. At this Workshop R. Davis considered for geoneutrino detection purposes two resonant reactions:

$$^{35}\text{Cl} \rightarrow ^{35}\text{S}, E_{res} = 0.17 \text{ MeV} \text{ and } ^{209}\text{Bi} \rightarrow ^{209}\text{Pb}, E_{res} = 0.64 \text{ MeV} \quad (5)$$

with subsequent radiochemical separation of radioactive ^{35}S and ^{209}Pb .

Marx ([15], 1969) considered various models of terrestrial U, Th and K distribution, estimated relevant $\bar{\nu}_e$ fluxes and recognized the importance of both resonant and inverse beta decay reactions for geoneutrino detection.

Krauss, Glashow and Schramm ([16], 1984) calculated radiogenic heat powers, $\bar{\nu}_e$ spectra and fluxes due to U, Th and K (Table 1). They assumed spherically symmetric distribution of radioactive isotopes in a 100 km thick outer layer of the Earth; thus their results correspond to some average point on the surface. Most attention in [16] is given to geoneutrino registration via resonant and inverse beta decay reactions; the cross-sections for large number of nuclei have been calculated. In the most favorable cases the transition probability (4) was found to be:

$$w \sim (3 - 6) \times 10^{-31} / \text{year}. \quad (6)$$

This is several thousand times lower than is observed in solar $\text{Ga} \rightarrow \text{Ge}$ experiments. . . “Detection of terrestrial antineutrinos will require sophisticated new technology. We can envision several generations of experiments aimed at measuring different parts of the antineutrino spectrum”. The first of these generations based on reaction (1) has surpassed in 2002 y the sensitivity level (6) and started detection of U and Th antineutrinos. Potassium antineutrinos still wait for their opportunity.

2 Radiogenic Heat - and Antineutrinos Models

Here we widely use information taken from book [1], encyclopedias, from Hofmann papers [17] and Fiorentiny group [18] publications. Modern models distribute the Earth's antineutrino- and radiogenic heat sources U, Th and K between the crust and the mantle. The Earth's structure schematically shown in Fig. 3 includes components:

- The crust. Thickness of the continental crust varies from ~ 70 km (at mountain sites like Hymalaya, Baksan etc.) to about 10 km, averaging around ~ 35 km. The continental crust contains a considerable part of the Earth's radioactivity. The oceanic crust is 5-6 km thick, covers about 3/4 of the Earth's surface; the U, Th and K concentrations are much lower than in the continental crust.
- The outer frontier of the Earth's core lies at the depth of 2900 km. It is believed to be in a molten state because transverse seismic waves do not penetrate inside it. Inside the molten core is (partially) crystallized inner core. It is assumed that both cores are built up of iron, nickel and some amount of lighter elements; it is believed (by the majority of geochemists) that there is no radioactivity in the core, because U, Th and K are chemically "incompatible" with the main components.
- The mantle, which is between the crust and molten core, is subdivided in two layers: the upper and the low. Volcanic outflows coming from the upper mantle show, that this layer is strongly "depleted" of radioactive elements. The lower mantle seems to be not so much depleted, but no systematic information is available on the subject.

How much of U, Th and K is contained in the Earth (crust + mantle)? It is believed that meteorites of a special type (carbonaceous chondrites) originate from the same substance that formed the primordial Earth 4.55 billion years ago. Starting from this point geochemists deduce the result:

$$a(\text{U}) = 2 \times 10^{-8} \text{g/g}, \quad a(\text{Th})/a(\text{U}) = 3.9, \quad (7)$$

where $a(\text{U})$ and $a(\text{Th})$ are element mass abundances.

Using (7) one can find total mass of Uranium $M(\text{U})$ and total mass of Thorium $M(\text{Th})$, contained in the crust + mantle and can calculate relevant radiogenic heat powers $H(\text{U})$ and $H(\text{Th})$:

$$\begin{aligned} \text{Crust + Mantle : } M(\text{U}) &= 0.8 \times 10^{17} \text{kg}, \quad M(\text{Th}) = 3.15 \times 10^{17} \text{kg}, \\ \text{Crust + Mantle : } H(\text{U}) &= 7.6 \text{ TW}, \quad H(\text{Th}) = 8.3 \text{ TW} \end{aligned} \quad (8)$$

Some features of U and Th decay are given in Tables 2, 3. The Earth in this model radiates $L_\nu = 1.1 \times 10^{25} \bar{\nu}_e/s$ emitted in U- and Th decay chains, which carry away 1.1 TW.

The outlined model (sometimes called Bulk Silicate Earth, BSE) is shared by a great majority of geochemists and geophysicists.

However, the BSE prescription does not work with K. Average K to U concentration ratio in carbonaceous chondrites is ~ 6 higher than is typical for terrestrial samples. This problem has been debated for decades. Two ideas have been proposed to explain K deficit in Earth's crust + mantle.

1. Tiny particles of which the Earth was formed 4.55 billion years ago had at that time higher temperatures than chondrites and had lost most part of original K through evaporation. In this case K contribution to the radiogenic heat is $H(\text{K}) \sim 2.5 \text{ TW}$.
2. Actually there is no K deficit at all; just the major part of primordial K has gone into the core. In this case $H(\text{K}) \sim 16 \text{ TW}$, most part of this power comes from the core. Recent laboratory experiments provide evidence that actually large quantity of K could enter the iron rich Earth's core [19].

Questioned is the theory that there is no U in the Earth's core. As already mentioned a self-sustaining fission reaction is supposed to burn there with a power release of 3–9 TW [4]. Also questionable is the type of meteorites, which ought to be used as a starting point for finding the amount of Earth's radioactivity [20].

In the BSE model the total radiogenic power $H_{\text{rad}} = H(\text{U}) + H(\text{Th}) + H(\text{K}) \approx 19 \text{ TW}$ is slightly lower than one half of the total Earth heat outflow ($H_{\text{tot}} \approx 40 - 42 \text{ TW}$). As an upper limit sometimes is considered a “fully radiogenic” model with U etc. masses increased by a factor ~ 2.2 so that $H_{\text{rad}} = H_{\text{tot}}$.

3 Strategy of Research, Geoneutrino Fluxes, Observables

Progress in the low energy $\bar{\nu}_e$ detection technique (the CHOOZ experiment, KamLAND and BOREXINO proposals) opened practical opportunities to detect geoneutrinos. In 1997-1998 yy Rothschild, Chen and Calaprice [21] and Raghavan et al. [22] proposed to use large target mass liquid scintillation detectors to investigate the geoneutrinos with the inverse beta decay (1) as a detection reaction.

Authors of [21] recognized that measurements are to be done at a number of geographical positions:

- in mountain regions where contribution of core radioactivity is dominant and geoneutrino intensity is expected to be maximal,
- in the ocean far from continents with dominant contribution from the mantle and minimal expected geoneutrion flux and
- at Kamioka site in Japan and at LNGS in Italy with an intermediate level of geoneutrino intensity.

Since 2002 y Fiorentini group in Italy has started extensive calculations of expected geoneutrino fluxes, detection rates and their dependence on the point of observation on the Earth's surface (see e.g. [18]).

In scintillation detectors geoneutrino energy spectrum at $E > 1.806$ MeV is measured using delayed coincidences between spatially correlated positron and neutron produced in reaction (1). $T \approx E - 1.806$ gives relation between positron kinetic energy T and the energy of incoming $\bar{\nu}_e$. In large target mass detectors the positron annihilation quanta are absorbed in the feducial volume and positron energy release E_{vis} is :

$$E_{vis} \approx E - 0.8 \text{ (MeV)}, \quad (9)$$

Thus the minimal positron energy release at the reaction threshold when $T = 0$ is $E_{vis(min)} = 1.02$ MeV.

The numbers of Uranium $N(U)$ and Thorium $N(Th)$ geoneutrino events produced in the scintillator target exposed to incident $\bar{\nu}_e$ fluxes $F(U)$ and $F(Th)$ are given by:

$$N(\text{U})/\text{year } 10^{32}\text{H} = 13.2 F(\text{U}) \times 10^{-6} \text{ cm}^{-2}\text{s}^{-1}$$

$$N(\text{Th})/\text{year } 10^{32}\text{H} = 4.1 F(\text{Th}) \times 10^{-6} \text{ cm}^{-2}\text{s}^{-1} \quad (10)$$

(1 160 ton of CH_2 based scintillator contains 10^{32} H atoms)

Geoneutrino fluxes $F(\text{U})$ from Uranium decay calculated in BSE model in [18] and [21] for a number of sites are shown in Fig. 4. In [18] higher values of Uranium abundances in the continental crust are assumed than those used in [21]. As a result differences in calculated fluxes for the same point of observation are rather large, which demonstrates good sensitivity of the neutrino method to the assumption on the distribution of radioactivity in the Earth. In Fig. 4 one can also clearly see a rapid decrease of the flux when the point of observation shifts from the mountains to the oceanic site.

The total numbers of the Uranium and Thorium events $N(\text{U}) + N(\text{Th})$ (Table 4) also demonstrate large scattering of predictions found in [18,21,22]. The expected number of geoneutrino events at BNO near the Elbrus mountain is close to that found for geographical maximum in Himalayas. As can be seen in Fig. 5 Uranium and Thorium events can be separated and thus the ratio of U/Th abundances measured. One also can see that at BNO the background coming from nuclear power reactors is sufficiently low.

The size and construction of the future detector and backgrounds require special consideration. Partially these issues have been considered in our recent publication on georeactor [6]. Good passive shield should protect the scintillator from the natural radioactivity of the surrounding rock, from PhM's glass and metallic support constructions. The anticoincidence system should effectively tag cosmic muons and showers. As already mentioned in the Introduction the muon flux at BNO is considerably lower than at Kamioka and LNGS (Fig. 1). Experience accumulated in KamLAND and BOREXINO projects shows that deepest purification of liquid scintillator can be achieved and extremely low level of radioactive contaminations can be reached, such as $\sim 3 \times 10^{-18}$ U g/g.

In [6] we have considered LS volume sufficiently large (10^{32} H atoms, 1.16 kton) to confirm or reject theory that a nuclear reactor is burning at the center of the Earth. The geoneutrino studies seem to require larger target mass detectors, may be as large as $(1 - 2) \times 10^{33}$ H atoms. Indeed, (a) the detection rates due to oscillation effect will be \sim two times lower than

those given in the Table 4; (b) good statistics is needed to separate U- and Th geoneutrinos (Fig. 5) and, finally, (c) we consider here a new generation experiment, which will operate after KamLAND. With an exposition $(50 - 100) \times 10^{32} \text{ H} \cdot \text{year}$ it would be possible to accumulate at BNO 2000-4000 geoneutrino events. With statistics like this one can try to investigate the angular distribution of incoming geoneutrinos, which can give valuable information on the location of U and Th masses in the interior of the Earth.

Conclusion

Uranium and Thorium distribution in the Earth's interior and relevant radiogenic heat can be found via geoneutrino observations at a number of geographical points.

The Baksan Neutrino Observatory is one of the most promising sites to build a massive antineutrino scintillation spectrometer for geoneutrino studies and also for investigations on low energy $\bar{\nu}_e$ and ν_e fluxes of natural origin aimed for obtaining information on their sources, which are otherwise inaccessible.

In 1984 y Krauss, Glashow, and Schramm wrote: "Neutrino and antineutrino astronomy and geophysics can open vast new windows for exploration above us and below". The first window is now opening at Kamioka. New windows can be opened at Baksan and elsewhere. Detector for Potassium antineutrinos is still to be invented.

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Table 1: Potassium, Thorium and Uranium in the Earth's lithosphere: Masses (M), fluxes of $\bar{\nu}_e$ (F) and radiogenic heat powers (H) according to [16]

Element	M 10^{17} kg	F $10^6 \text{ cm}^{-2}\text{s}^{-1}$	H 10^{12} W
U	0.80	3.5	9.6
Th	3.8	3.5	7.3
K	5.2×10^3	11	1.8
Total:		18	19

Table 2: Energy balance (MeV/decay) in equilibrium ^{238}U and ^{232}Th decay chains: Total energy E_{tot} , thermal (radiogenic) energy E_H and energy carried away by antineutrinos E_ν

	E_{tot}	E_H	E_ν
$^{238}\text{U} \Rightarrow ^{206}\text{Pb} + 8\ ^4\text{He} + 6\ \bar{\nu}_e$	51.7	47.7	4.0
$^{232}\text{Th} \Rightarrow ^{208}\text{Pb} + 6\ ^4\text{He} + 4\ \bar{\nu}_e$	42.7	40.0	2.3

Table 3: Specific radiogenic heat powers H , neutrino luminosities L_ν and radiated antineutrino powers W_ν

	$H, \text{ TW}/10^{17}\text{kg}$	$L_\nu, 10^{24}\text{s}^{-1}/10^{17}\text{kg}$	$W_\nu, \text{ TW}/10^{17}\text{kg}$
^{238}U	9.5	7.6	0.81
^{232}Th	2.6	1.6	0.15

Table 4: Expected rates of U + Th events at various sites (exposition 10^{32} H · year, no oscillations)

Site	Rothschild <i>et al.</i> * [21]	Raghavan <i>et al.</i> [22]	Fiorentini <i>et al.</i> [18]
Himalaya	65	-	112
Baksan	-	-	91
Gran Sasso	53	Ia: 134; Ib: 50	71
Kamioka	48	Ia: 75; Ib: 50	61
Hawaii	27	-	22

* Calculated using Eqs. (10) and $\bar{\nu}_e$ Fluxes from Ref. [21]

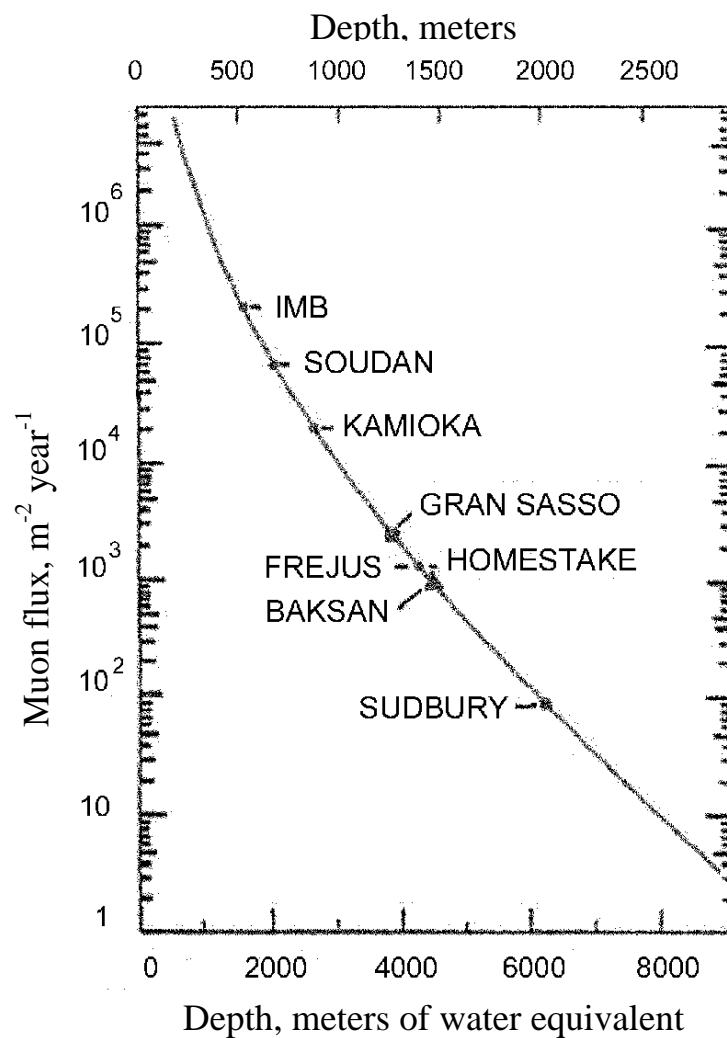


Figure 1. Muon flux underground (from V. Gavrin's talk at NANP-2003, <http://www.nanp.ru/2003/program.html>)

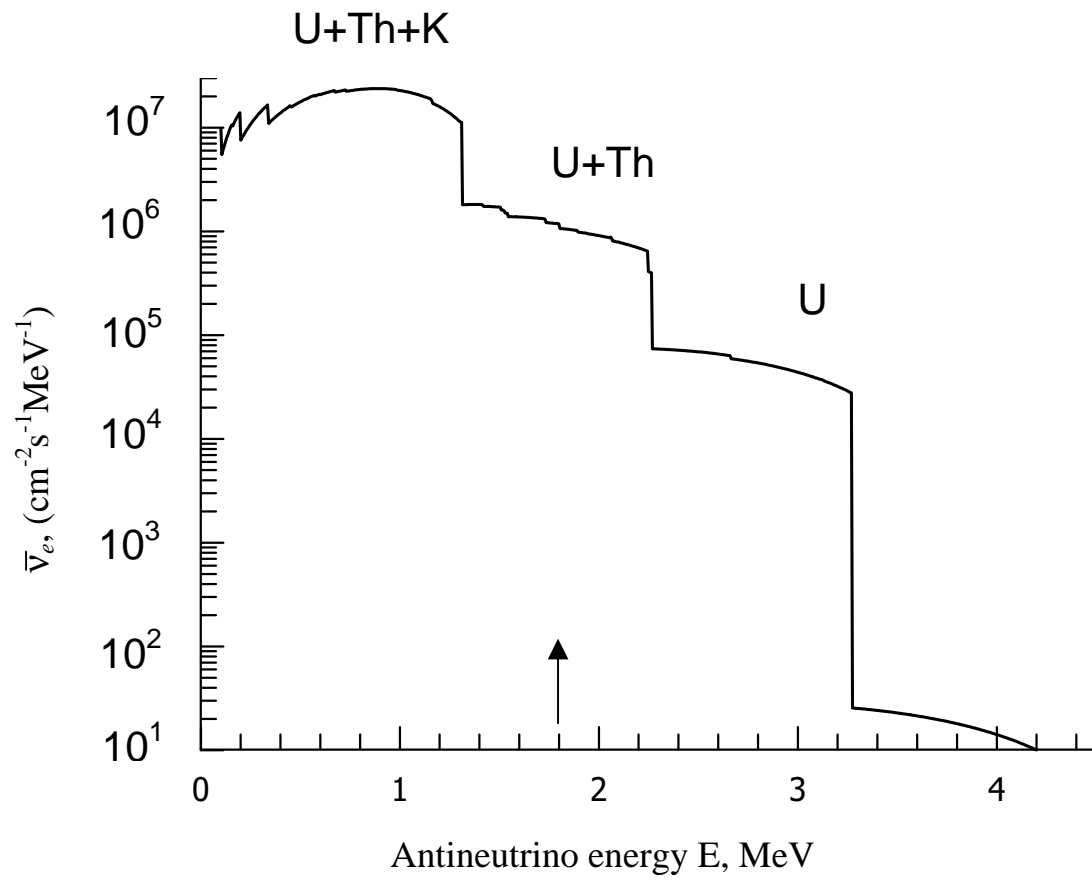


Figure 2. Typical U+ Th + K geoneutrino energy spectrum. The arrow shows threshold of reaction (1)

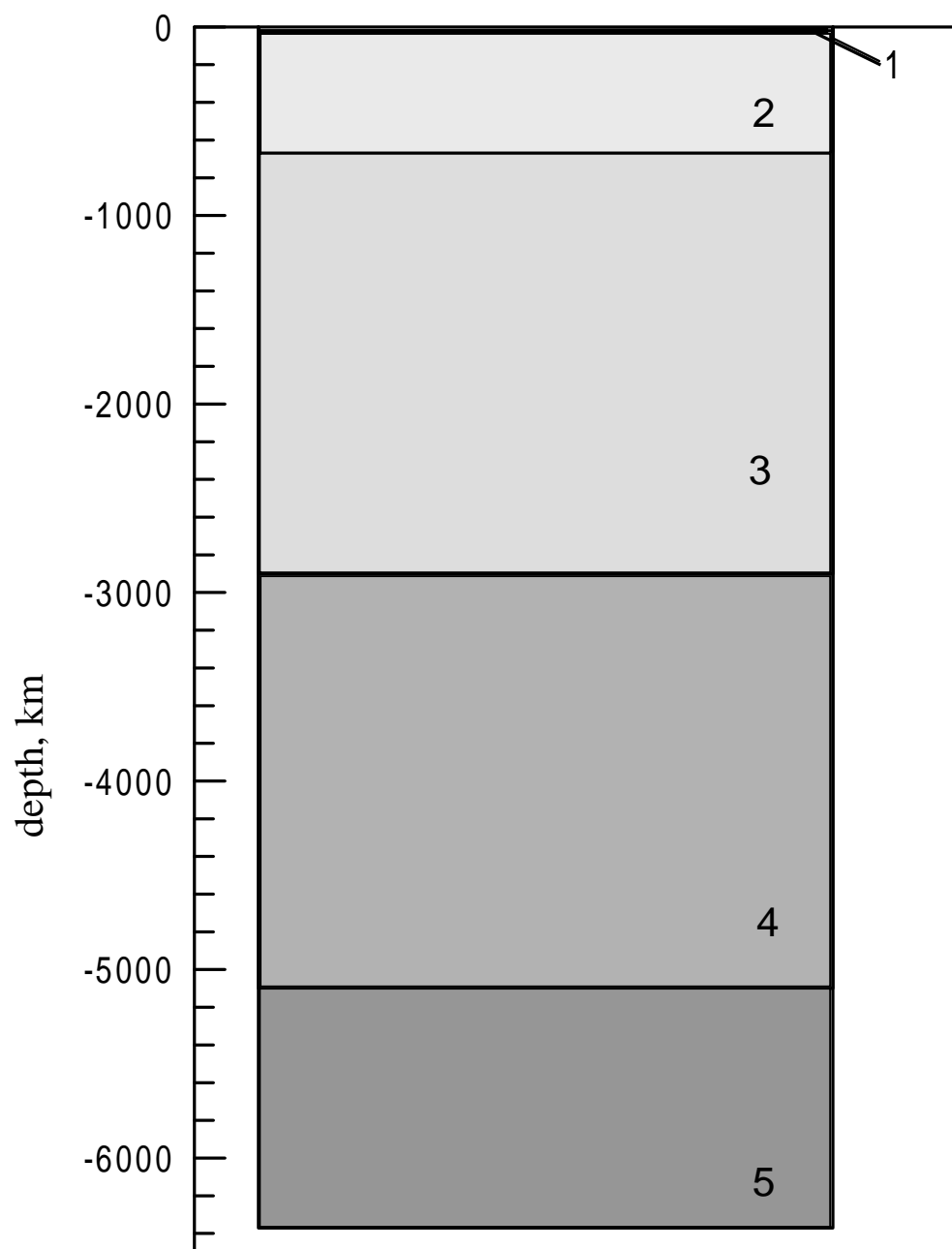


Figure 3. Internal structure of the Earth (schematic)

1 – crust , 2 – upper mantle, 3 – lower mantle, 4 – outer molten core, 5 – inner (solid) core.

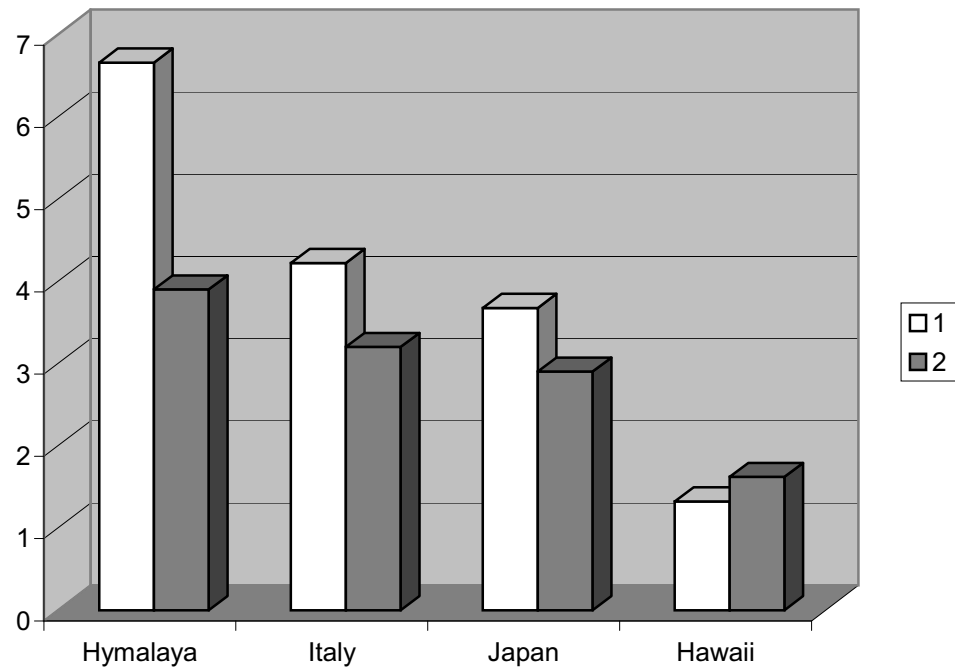


Figure 4. Calculated Uranium geoneutrino flux F ($10^6 \text{ cm}^{-2} \text{ s}^{-1}$) at different sites.
1 – Fiorentini *et al.* [18], 2 – Rothschild *et al.* [21].

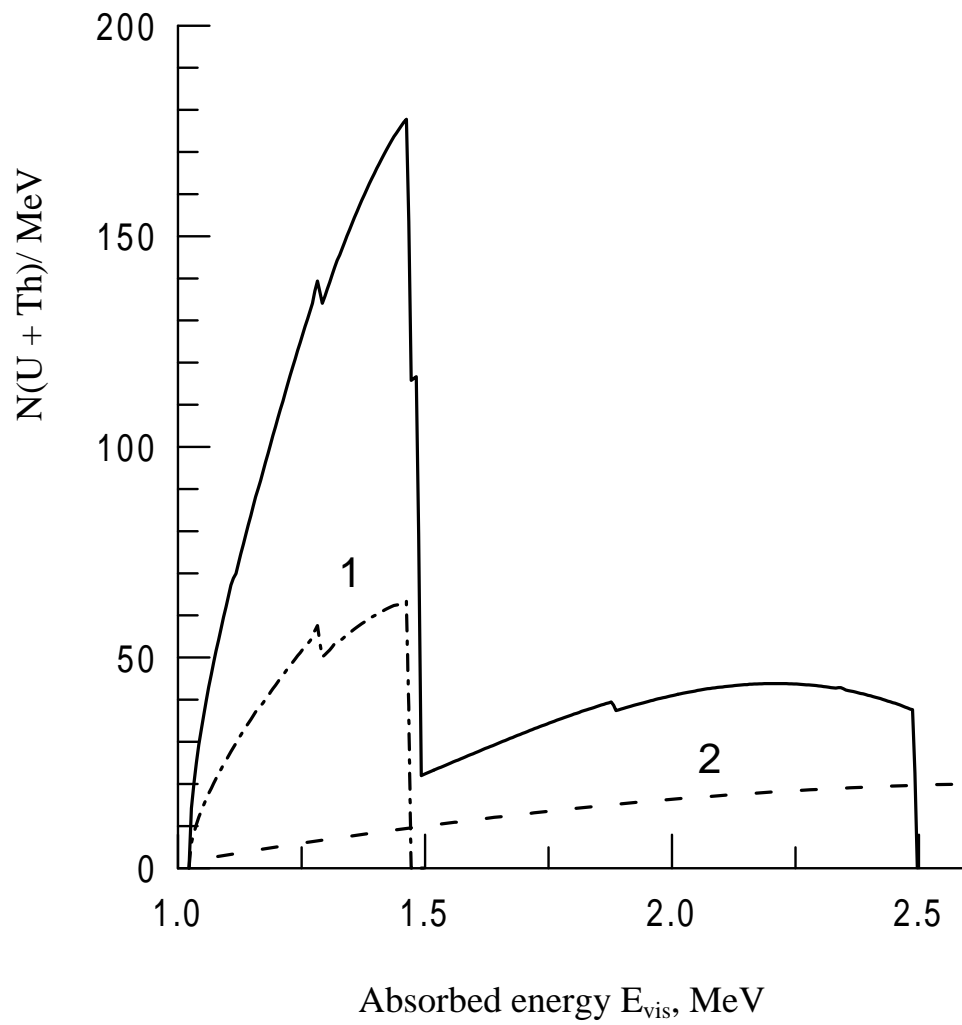


Figure 5 Expected geoneutrino-induced positron spectrum at Baksan,
(exposition 10^{32} H·year, no oscillations)
Solid line – U + Th, 1 – Th, 2 – signal from power reactors.